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Some relations between invariants of cyclotomic \mathbf{Z}_p -fields

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Abstract

In this paper, we show a basic inequality of Riemann-Hurwitz type for certain invariants (connected with the λ -invariants) of cyclotomic \mathbf{Z}_p -fields. As its application, if the Vandiver conjecture holds for p , then we have an upper bound of the λ -invariants of some cyclotomic \mathbf{Z}_p -fields containing $\exp(2\pi\sqrt{-1}/p)$.

Introduction

For a cyclotomic \mathbf{Z}_p -extension K of a number field K_0 with μ -invariant 0, let X_K (resp. \overline{X}_K) be the Galois group over K of its maximal abelian p -extension which is unramified (resp. unramified outside places dividing p) over K . We introduce some invariants of K/K_0 : let λ_K (resp. $\overline{\lambda}_K$) be the \mathbf{Z}_p -rank of X_K (resp. of the $\mathbf{Z}_p[[\text{Gal}(K/K_0)]]$ -torsion submodule of \overline{X}_K), and put $\lambda_K^- = \lambda_K - \lambda_{K \cap \mathbf{R}}$. In [5], Kida proved a Riemann-Hurwitz formula for λ^- of cyclotomic \mathbf{Z}_p -extensions of CM type, and this follows from a similar formula for $\overline{\lambda}$ of totally real cyclotomic \mathbf{Z}_p -extensions which is shown in [8]. Recently, in [6] and [9], Nguyen Quang Do and Wingberg proved a Riemann-Hurwitz formula for $\overline{\lambda}$ of general cyclotomic \mathbf{Z}_p -extensions under some assumptions which seemed to cannot be checked easily. We note that the results of [6] and [9] do not deduce immediately a formula for λ because the relation between λ and $\overline{\lambda}$ is not clear. The aim of this paper is to show a basic inequality of Riemann-Hurwitz type for certain invariants of cyclotomic \mathbf{Z}_p -extensions which deduces an inequality for λ .

Under the influence of genus theory, we consider an invariant

$$\lambda'_K = \dim_{\mathbf{F}_p}(X_K/pX_K).$$

Then it is easy to see that $\lambda'_K \geq \lambda_K$ and that $\lambda'_K = \lambda_K$ if and only if X_K is a free \mathbf{Z}_p -module. We will show that if K contains $\zeta_p = \exp(2\pi\sqrt{-1}/p)$ and L/K is a Galois p -extension unramified at all infinite places such that there is no unramified extensions between their intermediate fields, then

$$\lambda'_L - 1 \leq [L : K](\lambda'_K - 1) + \sum_v (e(v/K) - 1), \quad (1)$$

where v runs through all finite places of L , and $e(v/K)$ denotes the ramification index of v over K which will be well-defined and is equal to the local degree of v over K . In particular, if p does not divide the class number of $\mathbf{Q}(\cos(2\pi/p))$ and K is the cyclotomic \mathbf{Z}_p -extension of $\mathbf{Q}(\zeta_p)$, then we have

$$\lambda_L - 1 \leq [L : K](\lambda_K - 1) + \sum_v (e(v/K) - 1). \quad (2)$$

When p is odd and $L = K(p^{1/p^*})$, we show that X_L is a cyclic $A_q = \mathbf{Z}_p[[\text{Gal}(L/\mathbf{Q})]]$ -module annihilated by an element Φ of A_q which is a deformation of the sum of the p -adic L -functions, and that if (2) is an equality, then $X_L \cong A_q/(A_q\Phi)$. When $p = 2$, we give examples of real quadratic extensions L/K such that (1) is an equality (on the other hand, if the Greenberg conjecture [2] holds for L , then λ_L is always equal to 0).

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Throughout this paper, we put $\zeta_n = \exp(2\pi\sqrt{-1}/n)$ ($n \in \mathbf{N}$), and we consider any field as a subfield of \mathbf{C} . For a prime number p , we call K a *cyclotomic \mathbf{Z}_p -field* if K is a finite extension of the unique \mathbf{Z}_p -extension of \mathbf{Q} . Then any finite place of \mathbf{Q} has finitely many extensions in K , and K becomes a \mathbf{Z}_p -extension of a number field finite over \mathbf{Q} which we denote by $K = \bigcup_{n \geq 0} K_n$. For a cyclotomic \mathbf{Z}_p -field $K = \bigcup_{n \geq 0} K_n$, let X_K be a \mathbf{Z}_p -module which is the projective limit of the p -ideal class groups of K_n ($n \geq 0$) with respect to the norm maps, and let \widetilde{K} (resp. \widetilde{K}_n) be the maximal unramified abelian p -extension of K (resp. K_n). Then $\widetilde{K} = \bigcup_{n \geq 0} \widetilde{K}_n$, and hence by class field theory, $X_K \cong \text{Gal}(\widetilde{K}/K)$. We define $\mu_K = 0$ if X_K is a finitely generated \mathbf{Z}_p -module.

Let K be a cyclotomic \mathbf{Z}_p -field, and let L be a finite extension of K . Then we can take $K = \bigcup_{n \geq 0} K_n$ and $L = \bigcup_{n \geq 0} L_n$ such that $[L_n : K_n] = [L : K]$ for any n .

For a place v of L , we denote by $e(v|L_n/K_n)$ (resp. $f(v|L_n/K_n)$) the ramification index (resp. the relative degree) of $v|L_n$ over K_n , and let $g(v|L_n/K_n)$ be the number of places v' of L_n satisfying $v'|K_n = v|K_n$. If L is Galois over K , then for sufficiently large n , L_n is Galois over K_n and hence

$$e(v|L_n/K_n) \cdot f(v|L_n/K_n) \cdot g(v|L_n/K_n) = [L_n : K_n].$$

Proposition 1. Assume that $K \ni \zeta_p$ and that L/K is a Galois p -extension. Then for any place v of L , $\lim_{n \rightarrow \infty} e(v|L_n/K_n)$ and $\lim_{n \rightarrow \infty} g(v|L_n/K_n)$ exist, and $\lim_{n \rightarrow \infty} f(v|L_n/K_n) = 1$.

Proof. It is enough to show this proposition for finite places. From the assumption, there exists a sequence of field extensions:

$$K = M^0 \subset M^1 \subset \dots \subset M^k = L$$

such that M^{i+1}/M^i ($i = 0, \dots, k-1$) is a cyclic extension of degree p . Then for each i , $M^{i+1} = M^i(\sqrt[p]{\alpha_i})$ for some $\alpha_i \in (M^i)^\times$. Put $M_n^0 = K_n$ and $M_n^{i+1} = K_n(\sqrt[p]{\alpha_0}, \sqrt[p]{\alpha_1}, \dots, \sqrt[p]{\alpha_i})$ for $i = 0, \dots, k-1$. Then there exists $N \in \mathbb{N}$ such that for any $n \geq N$, $[L_n : K_n] = [L : K]$ and $\alpha_i \in (M_n^i)^\times$. Hence $((M_n^i)_v)$: the completion of M_n^i by v

$$\lim_{n \rightarrow \infty} g(v|M_n^{i+1}/M_n^i) = \begin{cases} 1 & \text{if } (M_n^i)_v \not\supset \sqrt[p]{\alpha} \text{ for any } n \\ p & \text{otherwise.} \end{cases}$$

Therefore,

$$\lim_{n \rightarrow \infty} g(v|L_n/K_n) = \prod_{i=0}^{k-1} \lim_{n \rightarrow \infty} g(v|M_n^{i+1}/M_n^i)$$

is well-defined.

We will show the rest of the statement. First we assume that v does not divide p . Then the completion L_v of L by v is a discrete valuation field, and hence $\lim_{n \rightarrow \infty} e(v|L_n/K_n)$ (resp. $\lim_{n \rightarrow \infty} f(v|L_n/K_n)$) is equal to the ramification index (resp. the relative degree) of L_v/K_v . Moreover, the latter is equal to 1 because the residue field of K_v is the unique \mathbb{Z}_p -extension of a finite field. Second we assume that v divides p . Then the p -power degree of $e(v|K_n/K_0)$ tends to infinity as $n \rightarrow \infty$, and hence there exists $N' \geq N$ such that one can take v -units $\beta_i \in M_n^i$ satisfying $M_n^{i+1} = M_n^i(\sqrt[p]{\beta_i})$ for any $n \geq N'$ and $i = 0, \dots, k-1$. Let k_n^i be the residue field of M_n^i at v , and put $\bar{\beta}_i = \beta_i \bmod(v)$. Then for any $n \geq N'$ and $i = 0, \dots, k-1$, $k_n^{i+1} = k_n^i(\sqrt[p]{\bar{\beta}_i}) = k_n^i$ because k_n^i is a finite field of p -power order. Therefore,

$$\lim_{n \rightarrow \infty} f(v|L_n/K_n) = \prod_{i=0}^{k-1} \lim_{n \rightarrow \infty} f(v|M_n^{i+1}/M_n^i) = 1,$$

and hence

$$\lim_{n \rightarrow \infty} e(v|L_n/K_n) = \frac{[L : K]}{\lim_{n \rightarrow \infty} g(v|L_n/K_n)}.$$

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Let K , L , and v be as in Proposition 1. Then we call $\lim_{n \rightarrow \infty} e(v|L_n/K_n)$ the *ramification index* of v over K , and denote this by $e(v/K)$. If $e(v/K) > 1$, then we call L/K is *ramified* at v . Let $P_f(L)$ (resp. $P_f(L_n)$) be the set of finite places of L (resp. L_n), and let $R(L/K)$ (resp. $R(L_n/K_n)$) be the set of places of L (resp. L_n) ramified over K (resp. K_n). By Proposition 1, for sufficiently large n , the restriction $v \mapsto v|L_n$ of places of L induces a bijection

$$R(L/K) \cap P_f(L) \cong R(L_n/K_n) \cap P_f(L_n),$$

and hence $R(L/K) \cap P_f(L)$ is a finite set. It is shown by Iwasawa [3, Theorem 3] that if L is a p -extension of a \mathbf{Z}_p -field K with $\mu_K = 0$, then $\mu_L = 0$. As for the λ' -invariant, we have the following results.

Theorem 1. *Let K be a cyclotomic \mathbf{Z}_p -field such that $K \ni \zeta_p$ and $\mu_K = 0$, and let L/K be a cyclic extension of degree p such that $R(L/K) \neq \emptyset$ and $R(L/K) \subset P_f(L)$. Then*

$$\lambda'_L - 1 \leq p(\lambda'_K - 1) + \sum_{v \in P_f(L)} (e(v/K) - 1).$$

Proof. Put $\Gamma = \text{Gal}(L/K)$, and let γ be a generator of Γ . Let \tilde{L} (resp. \tilde{L}_n) be the maximal unramified abelian p -extension of L (resp. L_n), and put $G = \text{Gal}(\tilde{L}/K)$, $X_L = \text{Gal}(\tilde{L}/L)$. Let $R(L/K) = \{v_0, v_1, \dots, v_s\}$, and for each $i = 0, \dots, s$, let \tilde{v}_i be a place of \tilde{L} dividing v_i with inertia subgroup I_i of G . Put $G_n = \text{Gal}(\tilde{L}_n/K_n)$ and $X_{L,n} = \text{Gal}(\tilde{L}_n/L_n)$, and let $I_{i,n}$ be the inertia subgroup of G_n at \tilde{v}_i . Since for sufficiently large n , $[L_n : K_n] = p$ and L_n/K_n is totally ramified at v_i , the injection $I_{i,n} \hookrightarrow G_n$ induces an isomorphism $I_{i,n} \cong G_n/X_{L,n}$. Therefore,

$$I_i = \varprojlim I_{i,n} \cong \varprojlim G_n/X_{L,n} = G/X_L = \Gamma,$$

and hence $G = X_L I_i$ ($i = 0, \dots, s$). For each i , let $\sigma_i \in I_i$ maps to γ , and $a_i \in X_L$ satisfying $\sigma_i = a_i \sigma_0$. Put $S = \gamma - 1$ and

$$\nu = 1 + \gamma + \gamma^2 + \dots + \gamma^{p-1} = \{(1 + S)^p - 1\}/S$$

which act on X_L . Since $\sigma_i^p = 1$ and $\sigma_i^p = \nu(a_i) \sigma_0^p$, $\nu(a_i) = 0$. Let M be the sub \mathbf{Z}_p -module of X_L generated by a_1, \dots, a_s . Since \tilde{K}/K is the maximal unramified

abelian subextension of \tilde{L}/K , $\text{Gal}(\tilde{L}/\tilde{K})$ is the closed subgroup of X_L generated by SX_L , I_0 , and a_1, \dots, a_s . Therefore,

$$X_K = G/\text{Gal}(\tilde{L}/\tilde{K}) \cong X_L/(M + SX_L),$$

and hence

$$0 \longrightarrow M/(M \cap SX_L) \longrightarrow X_L/SX_L \longrightarrow X_K \longrightarrow 0$$

is exact. Let $b_j \in X_L$ ($j = 1, \dots, \lambda'_K$) satisfying

$$X_K = \sum_{j=1}^{\lambda'_K} \mathbf{Z}_p \bar{b}_j \quad (\bar{b}_j = b_j \bmod (M + SX_L)).$$

Then

$$X_L/SX_L = \sum_{i=1}^s \mathbf{Z}_p a_i + \sum_{j=1}^{\lambda'_K} \mathbf{Z}_p b_j.$$

Since $S\nu = 0$ on X_L and $\nu(a_i) = 0$,

$$X_L = \sum_{k=0}^{p-2} \sum_{i=1}^s \mathbf{Z}_p S^k(a_i) + \sum_{l=0}^{p-1} \sum_{j=1}^{\lambda'_K} \mathbf{Z}_p S^l(b_j).$$

Therefore,

$$\lambda'_L - 1 \leq (p-1)s + p\lambda'_K - 1 = p(\lambda'_K - 1) + (s+1)(p-1).$$

Theorem 2. Let K be a cyclotomic \mathbf{Z}_p -field such that $K \ni \zeta_p$ and $\mu_K = 0$, and let $K = M^0 \subset M^1 \subset \dots \subset M^k = L$ be a sequence of cyclic extensions of degree p such that $R(M^{i+1}/M^i) \neq \emptyset$ and $R(M^{i+1}/M^i) \subset P_f(M^{i+1})$ for any $i = 0, \dots, k-1$. Then

$$\lambda'_L - 1 \leq [L : K](\lambda'_K - 1) + \sum_{v \in P_f(L)} (e(v/K) - 1).$$

Proof. We will show this theorem by the induction on k . Assume that there exist cyclotomic \mathbf{Z}_p -fields $K \subset M \subset L$ such that

$$\lambda'_M - 1 \leq [M : K](\lambda'_K - 1) + \sum_{v' \in P_f(M)} (e(v'/K) - 1),$$

and that L/M is a cyclic extension of degree p with $\emptyset \neq R(L/K) \subset P_f(L)$. Then by Theorem 1 and the above inequality,

$$\lambda'_L - 1 \leq [L : K](\lambda'_K - 1) + p \sum_{v' \in P_f(M)} (e(v'/K) - 1) + \sum_{v \in P_f(L)} (e(v/M) - 1).$$

By Proposition 1, $P_f(M)$ is a disjoint union of its subsets $P_1(M)$ and $P_2(M)$ consisting of finite places of M ramified in L and splitting in L respectively. Hence

$$\sum_{v \in P_f(L)} (e(v/K) - 1) = \sum_{v' \in P_1(M)} (pe(v'/K) - 1) + p \sum_{v' \in P_2(M)} (e(v'/K) - 1),$$

and

$$\begin{aligned} & \sum_{v' \in P_1(M)} (pe(v'/K) - 1) \\ &= p \sum_{v' \in P_1(M)} (e(v'/K) - 1) + (p - 1)|P_1(M)| \\ &= p \sum_{v' \in P_1(M)} (e(v'/K) - 1) + \sum_{v \in P_f(L)} (e(v/M) - 1). \end{aligned}$$

Therefore,

$$\lambda'_L - 1 \leq [L : K](\lambda'_K - 1) + \sum_{v \in P_f(L)} (e(v/K) - 1).$$

3

In what follows, let K be the cyclotomic \mathbf{Z}_p -extension of $\mathbf{Q}(\zeta_p)$. Then by a result of Ferrero-Washington [1], $\mu_K = 0$. Let h_p^+ denote the class number of $\mathbf{Q}(\cos(2\pi/p))$.

Theorem 3. *Assume that p does not divide h_p^+ , and let $K = M^0 \subset \dots \subset M^k = L$ be a sequence of cyclic extensions of degree p such that $R(M^{i+1}/M^i) \neq \emptyset$ and $R(M^{i+1}/M^i) \subset P_f(M^{i+1})$ for any $i = 0, \dots, k-1$. Then*

$$\lambda_L - 1 \leq [L : K](\lambda_K - 1) + \sum_{v \in P_f(L)} (e(v/K) - 1).$$

Proof. This follows from Theorem 2 and the result of Iwasawa which says that X_K is a free \mathbf{Z}_p -module (cf. [7, Theorem 10.16]).

Corollary 1. *Assume that p does not divide h_p^+ , and let v_p be the unique place of K dividing p . Let L/K a cyclic extension of degree p such that $R(L/K) \neq \emptyset$ and $R(L/K) \subset P_f(L)$, and let N and I be the endomorphisms of the unit group U_L of L defined by $N(a) = a^{1+\gamma+\dots+\gamma^{p-1}}$ and $I(a) = a^{\gamma-1}$ ($a \in U_L$) respectively, where γ is a generator of $\text{Gal}(L/K)$. Then*

$$\frac{|\text{Ker}(N)/\text{Im}(I)|}{|\text{Ker}(I)/\text{Im}(N)|} \geq \begin{cases} p & \text{if } v_p \text{ is unramified in } L \\ 1 & \text{if } v_p \text{ is ramified in } L. \end{cases}$$

Proof. Put

$$p^m = \frac{|\text{Ker}(I)/\text{Im}(N)|}{|\text{Ker}(N)/\text{Im}(I)|}.$$

Then by a result of Iwasawa [4, Theorem 6],

$$\lambda_L - 1 = p(\lambda_K - 1) + (m + 1)(p - 1) + \sum_{v \in P'_f(L)} (e(v/K) - 1),$$

where $P'_f(L)$ is the set of finite places of L not dividing p . Hence

$$m \leq \begin{cases} -1 & \text{if } v_p \text{ is unramified in } L \\ 0 & \text{if } v_p \text{ is ramified in } L. \end{cases}$$

4

In this section, assume that $p > 2$, and put $L = K(p^{1/p^k})$ for $k \in \mathbb{N}$.

Proposition 2. *The Galois extension L/K is of degree p^k , and there exists a unique place of L dividing p which is totally ramified over K .*

Proof. For $n \geq 0$, let C be the completion of $\mathbb{Q}(\zeta_{p^n})$ by the unique place of K dividing p . Then by Proposition 1, to prove this proposition, it is enough to show that $C(p^{1/p^i}) \neq C(p^{1/p^{i+1}})$ for any $i = 0, \dots, k-1$. On the contrary, assume that $C(\sqrt[p]{\alpha}) = C(\alpha)$ ($\alpha := p^{1/p^i}$) for some i . Then $\mathbb{Q}_p(\sqrt[p]{\alpha})/\mathbb{Q}_p(\alpha)$ is an abelian extension because $C(\alpha)/\mathbb{Q}_p(\alpha)$ is an abelian extension. Since $\sqrt[p]{\alpha} \notin \mathbb{Q}_p(\alpha)$, $\zeta_p \in \mathbb{Q}_p(\alpha)$, and hence $p^i = [\mathbb{Q}_p(\alpha) : \mathbb{Q}_p]$ is divisible by $p-1 = [\mathbb{Q}_p(\zeta_p) : \mathbb{Q}_p]$, which is a contradiction.

Corollary 2. *Assume that p does not divide h_p^+ . Then $\lambda_L \leq p^k \lambda_K$.*

Proof. This follows from Theorem 3 and Proposition 2.

Put $\Delta = \text{Gal}(\mathbb{Q}(\zeta_p)/\mathbb{Q})$, and regard Δ as a subgroup of $\text{Gal}(K/\mathbb{Q})$ by the Teichmüller character $\omega : \mathbb{F}_p^\times \rightarrow \mathbb{Z}_p^\times$ and the isomorphisms $\Delta \cong \mathbb{F}_p^\times$, $\text{Gal}(K/\mathbb{Q}) \cong \mathbb{Z}_p^\times$ induced from the Galois action on $\{\zeta_{p^n}\}_{n \in \mathbb{N}}$. For each $i = 0, 1, \dots, p-2$, put

$$\varepsilon_i = \frac{1}{|\Delta|} \sum_{\delta \in \Delta} \omega^{-i}(\delta) \cdot \delta \in \mathbb{Z}_p[[\text{Gal}(K/\mathbb{Q})]],$$

and for each $i = 3, 5, \dots, p-2$, let $L_p(s, \omega^{1-i})$ denote the p -adic L -function with character ω^{1-i} . Let γ and q be the elements of $\text{Gal}(L/\mathbb{Q}(\zeta_p))$ given by $\gamma(\zeta_{p^n}) =$

$\zeta_{p^n}^{p+1}$, $\gamma(p^{1/p^k}) = p^{1/p^k}$ and $q(\zeta_{p^n}) = \zeta_{p^n}$, $q(p^{1/p^k}) = \zeta_{p^k} p^{1/p^k}$ ($n \geq 0$) respectively. Then under the correspondences $\gamma \leftrightarrow 1+T$ and $q \leftrightarrow 1+S$, $\mathbf{Z}_p[[\text{Gal}(L/\mathbf{Q}(\zeta_p))]]$ is isomorphic to the quotient ring Λ_q of $\mathbf{Z}_p[[T, S]]_{\text{n.c.}}$ (: the non-commutative power series ring over \mathbf{Z}_p with variables T and S) by the relations $(1+T)(1+S) = (1+S)^{p+1}(1+T)$ and $(1+S)^{p^k} = 1$. Therefore, $A_q = \mathbf{Z}_p[[\text{Gal}(L/\mathbf{Q})]]$ satisfies

$$A_q = \bigoplus_{i=0}^{p-2} \varepsilon_i \mathbf{Z}_p[[\text{Gal}(L/\mathbf{Q}(\zeta_p))]] \cong \bigoplus_{i=0}^{p-2} \varepsilon_i \Lambda_q. \quad (3)$$

From the injection $\iota : \text{Gal}(K/\mathbf{Q}) \rightarrow \text{Gal}(L/\mathbf{Q})$ given by $\iota(\sigma)(p^{1/p^k}) = p^{1/p^k}$ ($\sigma \in \text{Gal}(K/\mathbf{Q})$), we can regard $\mathbf{Z}_p[[\text{Gal}(K/\mathbf{Q})]]$ as a sub \mathbf{Z}_p -algebra of A_q . Let \tilde{L} be the maximal unramified abelian p -extension of L , and let $\tau \in \text{Gal}(L/\mathbf{Q})$ act on $X_L = \text{Gal}(\tilde{L}/L)$ as $\tau(x) = \tilde{\tau}x\tilde{\tau}^{-1}$ ($\tau \in \text{Gal}(L/\mathbf{Q})$, $x \in X_L$) where $\tilde{\tau} \in \text{Gal}(\tilde{L}/\mathbf{Q})$ is a lifting of τ . Then this action is well-defined, and hence we can regard X_L as a left A_q -module.

Theorem 4. Assume that p does not divide h_p^+ . Then there exist $\Phi \in A_q$ and $z \in X_L$ which satisfy the following:

- (a) $A_q \ni \alpha \mapsto \alpha z \in X_L$ induces a surjective A_q -homomorphism $A_q/(A_q\Phi) \rightarrow X_L$.
- (b) If we put $\Phi = \sum_{i=0}^{p-2} \varepsilon_i F_i$ ($F_i \in \Lambda_q$) under the isomorphism (3), then

$$F_i|_{S=0, T=(1+p)^{i-1}} = \begin{cases} 1 & (i = 0, 1, 2, 4, \dots, p-3) \\ L_p(s, \omega^{1-i}) & (i = 3, 5, \dots, p-2). \end{cases}$$

Moreover, if $\lambda_L = p^k \lambda_K$, then the above homomorphism $A_q/(A_q\Phi) \rightarrow X_L$ is an isomorphism.

Proof. Put $\Lambda = \mathbf{Z}_p[[T]]$ and $A = \mathbf{Z}_p[[\text{Gal}(K/\mathbf{Q})]]$. Then under the correspondence $\gamma \leftrightarrow 1+T$, $\mathbf{Z}_p[[\text{Gal}(K/\mathbf{Q}(\zeta_p))]]$ is isomorphic to Λ , and hence

$$A = \bigoplus_{i=0}^{p-2} \varepsilon_i \mathbf{Z}_p[[\text{Gal}(K/\mathbf{Q}(\zeta_p))]] \cong \bigoplus_{i=0}^{p-2} \varepsilon_i \Lambda. \quad (4)$$

By Proposition 2 and the proof of Theorem 1, $X_K \cong X_L/SX_L$. Let $\sigma \in \text{Gal}(K/\mathbf{Q})$ act on X_K as $\sigma(x) = \tilde{\sigma}x\tilde{\sigma}^{-1}$ ($\sigma \in \text{Gal}(K/\mathbf{Q})$, $x \in X_K$), where $\tilde{\sigma} \in \text{Gal}(\tilde{K}/\mathbf{Q})$ is a lifting of σ . Then this action induces an action of A on $X_K \cong X_L/SX_L$ compatible with the A_q -module structure of X_L . By a result of Iwasawa (cf. [7, Theorem 10.16]), there exist $\phi \in A$ and $z_0 \in X_K$ such that $A \ni \alpha \mapsto \alpha z_0 \in X_K$ induces an A -isomorphism $A/(A\phi) \xrightarrow{\sim} X_K$, and that if we put $\phi = \sum_{i=0}^{p-2} \varepsilon_i f_i$ ($f_i \in \Lambda$) under

the isomorphism (4), then $f_i \notin p\Lambda$ and

$$f_i|_{T=(1+p)^s-1} = \begin{cases} 1 & (i = 0, 1, 2, 4, \dots, p-3) \\ L_p(s, \omega^{1-i}) & (i = 3, 5, \dots, p-2). \end{cases}$$

Let z be an element of X_L such that $z \bmod(SX_L) = z_0$. Then by Nakayama's lemma, $A_q\alpha \mapsto \alpha z \in X_L$ is a surjective A_q -homomorphism. Since $\phi(z) \in SX_L$, there exists $\Phi \in A_q$ such that $\Phi(z) = 0$ and $\Phi \equiv \phi \bmod(SA_q)$, and hence we have a surjective A_q -homomorphism $A_q/(A_q\Phi) \rightarrow X_L$. For each i , let F_i be the element of Λ_q such that $\varepsilon_i\Phi = \varepsilon_iF_i$ under (3). Then $\Phi = \sum_{i=0}^{p-2} \varepsilon_iF_i$ and $F_i \equiv f_i \bmod(S\Lambda_q)$. Hence $A_q/(A_q\Phi)$ is a \mathbb{Z}_p -module with $p^k\lambda_K$ generators $S^a\varepsilon_iT^b$ ($0 \leq a < p^k, 0 \leq i < p-1, 0 \leq b < \text{rank}_{\mathbb{Z}_p}(\Lambda/\Lambda f_i)$). Therefore, if $\lambda_L = p^k\lambda_K$, then the homomorphism $A_q/(A_q\Phi) \rightarrow X_L$ is an isomorphism.

5

In this section, we assume that $p = 2$ and study the λ' -invariants of certain cyclotomic \mathbb{Z}_2 -fields.

Theorem 5. *Let p_1, \dots, p_t be primes such that $p_i \equiv 5 \pmod{8}$ ($i = 1, \dots, t$), and put $m = p_1 \cdots p_t$ and $L = K(\sqrt{m})$. Then $\lambda'_L = t - 1$.*

Proof. Since K/\mathbb{Q} is totally ramified at 2 and $\mathbb{Q}(\sqrt{m})/\mathbb{Q}$ is unramified at 2, $L/\mathbb{Q}(\sqrt{m})$ is totally ramified at any place of $\mathbb{Q}(\sqrt{m})$ dividing 2. Let I_0 be the ideal class group of $\mathbb{Q}(\sqrt{m})$ denoted as an additive group. Then the canonical homomorphism $X_L/2X_L \rightarrow I_0/2I_0$ is a surjection. By genus theory, $I_0/2I_0 \cong \text{Gal}(\mathbb{Q}(\sqrt{p_1}, \dots, \sqrt{p_t})/K)$, and hence $\lambda'_L \geq t - 1$. Since each p_i generates $1 + 4\mathbb{Z}_2 \cong \text{Gal}(K/\mathbb{Q})$, p_i is unramified and remains prime in K . Hence L/K is only ramified at p_i ($i = 1, \dots, t$). Therefore, by Theorem 2,

$$\lambda'_L - 1 \leq [L : K](\lambda'_K - 1) + \sum_{v \in P_f(L)} (e(v/K) - 1) = t - 2,$$

and hence we have $\lambda'_L = t - 1$.

Corollary 3. *For each $n \geq 0$, let K_n/\mathbb{Q} the unique subextension of K/\mathbb{Q} with Galois group $\mathbb{Z}/2^n\mathbb{Z}$. Let m be as above, and let I_n be the ideal class group of $K_n(\sqrt{m})$. Then $|I_n/2I_n| = 2^{t-1}$.*

Proof. Since $K(\sqrt{m})/\mathbb{Q}(\sqrt{m})$ is totally ramified at any place of $\mathbb{Q}(\sqrt{m})$ lying above 2,

$$|I_0/2I_0| \leq |I_n/2I_n| \leq |X_{K(\sqrt{m})}/2X_{K(\sqrt{m})}|.$$

Therefore, by Theorem 5, we have $|I_n/2I_n| = 2^{t-1}$.

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